METHOD AND APPARATUS FOR TWO-USER JOINT DEMODULATION IN A SYSTEM HAVING TRANSMIT DIVERSITY

BACKGROUND OF THE INVENTION

5   The performance of a wireless communication system can be improved through the addition and exploitation of signal "diversity" at one or more points in the system. A signal is said to have diversity when it can be divided into multiple (usually two) different signals, each carrying the same information, but differing in some respect. The term "diversity" typically refers to spatial diversity that results

10   when a signal is sampled at, or transmitted from two different points in space, as by two antennas. In such an arrangement, the signal is said to have a different "diversity branch" for each antenna.

Transmit diversity is an important method for improving reception in the situation where limited diversity is available at the receiver, for example, in the

15   case of single-antenna handsets. If the handset has *a priori* knowledge of the transmit diversity scheme, the receiver in the handset can use the knowledge to demodulate a signal more effectively in the presence of noise. A space-time block code is used under the assumption of flat channels to achieve the same diversity benefit as would be obtained by maximal ratio combining of signals from two an-

20   tennas at the receiver. This approach can be extended for dispersive channels.

FIG. 1 illustrates the approach. Base station 101 transmits from two antennas simultaneously. In FIG. 1, two symbols, a_1 and a_2, are transmitted from two antennas so that the received signal combines the symbols in a favorable manner. During the first transmission, a_1 is transmitted from antenna 102 and a_2

25   is transmitted from antenna 103. During the next transmission, $-a_2{}^*$ is transmitted

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from antenna 102 and a_1^* is transmitted from antenna 103. Assuming that fading is flat for each signal, Nyquist signaling is used so that there is no inter-symbol interference (ISI) from the filtered and sampled signal, and the channel is constant over the two symbol transmissions. The two received, sampled signals, r_1 and r_2

5   can be described by the following vector/matrix form. In the following discussion, lowercase variables denote vector quantities and uppercase variables denote matrix quantities:

$$\begin{bmatrix} r_1 \\ r_2 \end{bmatrix} = \begin{bmatrix} a_1 & a_2 \\ -a_2^* & a_1^* \end{bmatrix} \begin{bmatrix} c_1 \\ c_2 \end{bmatrix} + \begin{bmatrix} \omega_1 \\ \omega_2 \end{bmatrix}$$

where c_1 and c_2 represent channel estimates between the two antennas and

10   wireless terminal 104 of FIG. 1, and ω_1 and ω_2 represent extraneous noise. For some processing, it is useful to reformulate the channel estimates and symbol representations using r_2^* in place of r_2, yielding:

$$\begin{bmatrix} r_1 \\ r_2^* \end{bmatrix} = \begin{bmatrix} c_1 & c_2 \\ c_2^* & -c_1^* \end{bmatrix} \begin{bmatrix} a_1 \\ a_2 \end{bmatrix} + \begin{bmatrix} \omega_1 \\ \omega_2^* \end{bmatrix}.$$

For the kth pair of transmitted symbols $\{a_1(k); a_2(k)\}$, and the kth received sample

15   pair $\{r_1(2k); r_2(2k+1)\}$, the above equations are written as:

$$y_k = A_k c_k + v_k,$$

$$r_k = C_k a_k + \omega_k$$

respectively.

An example receiver used with the transmit diversity system shown above

20   is illustrated in FIG. 2. The receiver includes a vector data generator, 201, a channel estimation unit, 202, and a detector unit, 203. The signal stream is represented by $\{a(k)\}$, a portion of which, s_p, is used for channel estimation. The sym-

bols a_p represent symbols from a known pilot field or a known pilot carrier for use in obtaining the estimated channel coefficients. The received samples $\{r(k)\}$ are used to first form the vector y_p, which corresponds to the known pilot symbols. These received samples are used to estimate the channel coefficients $\hat{c}$. For ex-

5   ample, the channel coefficients can be obtained via least-squares estimation since the symbol data are known. The estimate, $\hat{c}_{LS}$ is given by:

$$\hat{c}_{LS} = (A_p^H A_p)^{-1} A_p^H y_p.$$

This equation reduces to:

$$\hat{c}_{LS} = A_p^H y_p,$$

10   in the case of flat fading and under the assumption that:

$$|a_1|^2 = |a_2|^2 = 1.$$

Note, there may be more than one known symbol pair, and $\hat{c}_{LS}$ can be easily modified to account for this, under the assumption that the channel is fixed for an estimation period. Once $\hat{c}_{LS}$ is estimated, then the received sample pair r_k corre-

15   sponding to the unknown transmitted symbol pair a_k is used to detect these symbols. In the case that no known pilot symbols exist, the above estimation approaches can be used iteratively to generate estimates of the channel and detected symbol values.

Increasingly, receiving systems must demodulate and extract information

20   from two users (transmitters) occupying the same bandwidth or channel. In some cases, both signals contain desired information. More typically however, one user is transmitting a desired signal, and a second user represents co-channel interference. Co-channel interference has become a significant problem as the population density of people using wireless, cellular communication devices increases.

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Because of the traffic demand, it is necessary to re-use channels more frequently on a geographic basis. Joint demodulation schemes have been used successfully to demodulate signals from two users on the same channel. Such schemes do not make use of diversity and only work when the signal-to-noise ratio is fairly

5   high. There are also co-channel interference canceling methods that make use of diversity at the receiver.

BRIEF SUMMARY OF THE INVENTION

The present invention provides methods and apparatus for joint
10   demodulation of signals from two users or transmitters on the same channel. The method of the invention exploits transmit diversity employed by at least one of the users. In one embodiment of the invention, symbol detection and channel estimation are performed in block or batch fashion. The received signal corresponds to a plurality of transmitted symbol sequences or blocks, originating

15   from both a first user and a second user. A stored symbol sequence corresponding to the first user, the first-user symbol sequence, as well as a stored symbol sequence corresponding to the second user, the second-user symbol sequence, are initialized, possibly through a semi-blind initialization procedure. Stored channel estimates are also initialized. In a block-by-block, iterative

20   fashion, received first-user symbol sequences and second-user symbol sequences are jointly and iteratively detected using the channel estimates, and based on the use of transmit diversity by at least one of the users. Detected sequences are used to update stored sequences as all sequences are demodulated. Channel estimates may also be updated on a block-by-block basis,

unless they are available from another source, such as an alternate pilot carrier in a code division multiple access (CDMA) system.

In another embodiment, symbols are updated, and channel estimates are updated, if necessary, recursively on a symbol-by-symbol basis. The received signal corresponds to a stream of a plurality of transmitted symbols from each user. A specific first-user symbol and a specific second-user symbol are detected at each of a plurality of symbol times, and stored symbols are updated. The detection process can use previously detected symbols as well as channel estimates. Again, joint detection makes use of transmit diversity by at least one of the transmitting users. Channel estimates can be updated at each current symbol time using channel tracking. If the signals from the first user and the second user are asynchronous, detection can be accomplished through reference to a pulse-shape component.

A receiving system which implements the invention includes a channel estimation unit operable to produce channel estimates for the first user and the second user, and a detector unit operatively connected to the channel estimation unit. The detector unit is operable to jointly detect a first-user symbol sequence and a second-user symbol sequence or first-user and second-user symbols at specific times. The receiving system may also include initialization logic. The detector unit may include a symbol update unit. In one embodiment, the symbol update unit and channel estimation unit are made up of interconnected reformulation operators and conjugation operators which can perform complex conjugate operations, as well as interconnected multipliers and adders. These components may be implemented in hardware, microcode, software, or a

combination, and form the means to carry out the invention. In one embodiment they form at least a portion of the baseband logic of a processor controlled, wireless terminal.

5   BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a diagram illustrating the concept of transmit diversity through the use of two antennas.

FIG. 2 is a block diagram of a prior-art receiver that makes use of transmit diversity.

10   FIG. 3 is a flowchart illustrating the method of the invention according to one embodiment.

FIG. 4 is a flowchart illustrating the method of the invention according to one embodiment.

FIG. 5 is a flowchart illustrating a method of blind initialization that can be

15   used in conjunction with the invention.

FIG. 6 is a flowchart illustrating the method of the invention according to another embodiment.

FIG. 7 is a flowchart that illustrates the operation of a detector unit according to an embodiment of the invention.

20   FIG. 8 is a signal processing flow diagram that illustrates a symbol update unit that may be used within the detector unit of FIG. 7.

FIG. 9 illustrates the operation of a channel estimation unit according to an embodiment of the invention in flowchart form.

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FIG. 10 is a signal processing flow diagram that illustrates the operation of a channel estimation unit according to the invention.

FIG. 11 is a flowchart that illustrates the operation of a detector unit that handles inter-symbol interference (ISI) according to an embodiment of the inven-

5 tion.

FIG. 12 is a signal processing flow diagram that illustrates the operation of a symbol update unit that handles ISI according to an embodiment of the invention.

FIG. 13 is a flowchart that illustrates channel tracking according to an em-

10 bodiment of the invention.

FIG. 14 is a signal processing flow diagram that further illustrates channel tracking according to an embodiment of the invention.

FIG. 15 is a block diagram of a mobile terminal that makes use of the present invention.

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DETAILED DESCRIPTION OF THE INVENTION

The present invention is typically embodied in a receiving system for a communication network where information is transmitted and received as a stream of symbols modulated onto a carrier wave. One example would be a net-

20 work employing time domain multiplexed access (TDMA). The embodiments disclosed are not restricted to any particular standard, however. The well-known Global System for Mobile (GSM) communication system is one example of a TDMA system which might employ the invention. The invention can also be used in a wireless data network employing code division multiplexed access (CDMA).

It should also be understood that not every feature of the receiving system described is necessary to implement the invention as claimed in any particular one of the appended claims. Various elements of receivers are described to fully enable the invention. It should also be understood that throughout this disclosure, where a process or method is shown or described, the steps of the method may be performed in any order or simultaneously, unless it is clear from the context that one step depends on another being performed first.

Some of the diagrams, which are used to illustrate the inventive concepts, are shown in software flowchart form, while others are shown as block diagrams and signal processing flow diagrams with various operators. The particular form of illustration is selected in each case to aid in understanding the invention. It is to be understood that the concepts discussed can be implemented in hardware or software. For example, a flowchart which is described as a detector unit or a detection method can be thought of as illustrating an algorithm performed by software, or the operation of a specific piece of hardware, such as an application specific integrated circuit (ASIC) that performs the illustrated task.

Finally the usage of terms such as "updating" and "initializing" typically refer to updating symbols or vectors stored or being stored in order to be operated on, decoded, or demodulated. The term user, as in first user and second user is colloquially being used to refer to a transmitter or sender of information, notwithstanding that most aspects of the invention are being implemented in a receiver or a receiver portion of a transceiver in a communication system.

The invention consists of the use of joint detection of at least two users to improve performance. In this approach, the objective is to minimize the quantity:

$$|r - \hat{r}(a,b)|^2$$

under the same assumptions as the single user case, to obtain values for new estimates for users a and b using:

$$a,b = \arg\min_{a,b} |r - \hat{r}(a,b)|^2.$$

5   An equivalent log-likelihood to be used for detection is:

$$\gamma = \mathrm{Re}\{a^H \gamma_a + b^H \gamma_b - a^H H b\}$$

where $H = C^H G$ and the above equation needs to be maximized.

Channel estimates can be obtained via least-squares estimation if the symbol data are known. In the case of flat fading, and assuming $|a|^2 = 1$, they re-

10   duce to:

$$\hat{c}_{LS} = A^H y$$

For the two-user scenario, with flat fading, the estimate for two user's channels, c and g, becomes:

$$\begin{bmatrix} \hat{c} \\ \hat{g} \end{bmatrix}_{LS} = \begin{bmatrix} A^H \\ B^H \end{bmatrix} y$$

15   and this equation shows each user interfering with the other user's channel estimate. An alternative estimation technique is the least-squares estimate with the interfering term removed from the received signal. Now, the estimates for each user's channel can be found using:

$$\hat{c}_{LS} = A^H(y - Bg),$$

20    $$\hat{g}_{LS} = B^H(y - Ac).$$

Since the interfering users channel estimate must be known in order to find the new estimate, values from prior iterations can be used to calculate new estimates.

One approach is to calculate the single-user estimates using the received signal with the interfering users term removed. Equations for these estimates are written as:

$$\hat{a} = \frac{1}{\alpha} C^H (r - Gb) \,,$$

5        $$\hat{b} = \frac{1}{\beta} G^H (r - Ca) \,.$$

An assumption is made that the channel estimates for both users are known and prior estimates of the symbol values are available from some prior iteration. The above procedure provides continuous value estimates for the symbols, which may be quantized (hard-detected) to the closest transmit symbol. The channel estima-

10   tion and detection steps are iteratively computed until some convergence criterion is met or some maximum number of iterations is reached.

Another iterative approach can be used to compute the maximum *a posteriori* estimate of the possible transmit symbols. This approach is described in U.S. Patent Number 5,887,035, which is incorporated herein by reference.

15   One embodiment of the invention is based on a two-user situation in which the base stations are synchronized. This can easily be accomplished if the system is designed to allow for joint demodulation according to the invention. It is also the case if two users are transmitting from the same base station. In this case, the received signal can be written as:

20        $$r_k = C_k a_k + G_k b_k + \omega_k$$

where b_k is the vector of symbols transmitted from a second base station and G_k is the corresponding channel response. Different signals are transmitted from the multiple transmit antennas and channel estimates will contain the effects of any

transformation from the originating signal stream to the multiple antennas.

For this example, a form of joint detection is illustrated which assumes that both signals use transmit diversity, the medium response is flat faded, channel coefficients are not known, and there are no training symbols. To address this problem, an iterative solution to two suboptimal problems, detection and channel estimation is used. The cases where some of the above quantities are known require some modifications to the approach that can easily be accomplished by one of ordinary skill in the art.

Iteration is used to address the transmit diversity problem when multiple users (desired and interfering) are present. Iteration can be performed in a block (i.e. batch) mode, or in a recursive mode of operation. FIG. 3 is a flowchart illustrating one embodiment of the block mode. In this embodiment, a detector unit performs block detection at 301 for the symbols:

$$\hat{a} = \{\hat{a}_1,...,\hat{a}_K\} \text{, and}$$

$$\hat{b} = \{\hat{b}_1,...,\hat{b}_K\} \text{,}$$

given channel estimates:

$$\hat{c} = \{\hat{c}_1...\hat{c}_K\} \text{, and}$$

$$\hat{g} = \{\hat{g}_1,...\hat{g}_K\} \text{.}$$

The terms $\tilde{a}$ and $\tilde{b}$ are either initial values for the first iteration or prior detected values during subsequent iterations. In either case these can be referred to as "previous" values, simply meaning they are already stored and available. These values can be initially set at the initialization step, 300. Initially setting these values to zero results in single-user detection for the first pass of the detector unit. In this example, the channel estimates are represented as complete sequences;

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however, a small set of channel estimates may be used when the channel is not time-varying or only slowly time-varying.

At step 302 of FIG. 3, the values of $\hat{c}$ and $\hat{g}$ are copied to $\tilde{c}$ and $\tilde{g}$, respectively for further processing in a channel estimation unit at step 303, where new channel estimates are computed. At step 305 a determination as to whether to perform another iteration is made. If another iteration is to be performed, the receiver copies the values $\hat{a}$ and $\hat{b}$ to $\tilde{a}$ and $\tilde{b}$, respectively at step 304. The detector unit calculates the values of $\hat{a}$ and $\hat{b}$ with $\hat{c}$ and $\hat{g}$ fixed. The values of $\hat{a}$, $\hat{b}$, $\tilde{a}$ and $\tilde{b}$ may be either hard or soft values.

FIG. 4 shows a similar embodiment, but initial values are now $\hat{a}$, $\hat{b}$, $\tilde{c}$ and $\tilde{g}$. Setting $\tilde{c}$ and $\tilde{g}$ to have zero initial values at initialization step 400 forces channel estimation at step 403 to perform single-user channel estimation for the first iteration. The rest of the processes are the same, with steps 401, 402, 404, and 405 being essentially the same processes that take place in steps 301, 302, 304, and 305 of FIG. 3. This embodiment is similar to the one shown in FIG. 3, but the iterative algorithm has different starting and termination points.

In the algorithm of FIG. 3, if the channel estimation unit 303 is skipped, then iteration only executes detection at step 301. This approach could be used when channel estimates are known or can be obtained by other means (such as the use of alternate pilot channels in a CDMA system). Similarly, in the second embodiment, if detection at step 401 is skipped during iteration, then only channel estimation at step 403 is executed. This might occur, for example, while detecting known pilot symbols that are being used for initial channel estimation.

The initialized values are assumed to be known in the above examples.

However, it may be the case that the second user signal is an interferer and the values corresponding to the interferer are unknown. FIG. 5 illustrates a semi-blind initialization procedure that can be used in this case. Assuming that $\hat{a}$ is known and can be initialized at step 500, the single user channel estimate $\hat{c}$ is computed

5 at step 501. Next, some rough estimate of $\hat{g}$ is generated at step 502. Then $\hat{a}$ is copies to $\tilde{a}$ at step 503. $\tilde{b}$ is set to zero and the initial conditions are output at 504.

The rough estimate of $\hat{g}$ discussed above can be obtained by training the desired user's channel estimate over known symbols corresponding to the desired

10 user, while using a sequence estimator to compute the channel estimate for the interfering user. Such an approach is described in U.S. Patent 6,304,618 which is incorporated herein by reference.

Rather than use a block estimation approach, an embodiment that uses recursive estimation can also be used. FIG. 6 shows a flowchart for the update at

15 symbol time k. Steps 601 through 605 are similar to the corresponding steps 301-305 in FIG. 3, however, detection and channel estimation units only operate on the kth symbol or channel estimation term. At step 606 an update is made of the channel estimates from the *k*th to the (*k*+1)st symbol time. Known, conventional channel tracking techniques may be used to predict the channel estimates from

20 one time to a future time. A recursive embodiment corresponding to the block approach shown in FIG. 4 can also be developed but is not shown here.

In the case of recursive detection where the signals are synchronous, the detection at each symbol time can be performed separately. There are multiple ways to do this, and one of ordinary skill in the art can select the appropriate way

for a proposed system. For the kth symbol time, the problem is to find the values

of $\hat{a}_k$ and $\tilde{b}_k$ using the equation:

$$\hat{a}_k, \hat{b}_k = \arg\min_{ak,bk} |\, r_k - \hat{r}_k(c_k, g_k)\,|^2 \,.$$

An equivalent log likelihood to be used for detection is:

5 $$\gamma = \operatorname{Re}\{a^H \gamma_a + b^H \gamma_b - a^H H_k b\}\,,$$

where $H_k = C_k^H G_k$. The object here is to detect the symbol from the first and sec-

ond user at the current symbol time that maximizes the above equation. Although

this can be done directly, each symbol can no longer be detected independently,

and so the complexity of the detection procedure is significant.

10   A lower complexity approach is to calculate the single-user estimates using

the received signal with the interfering user terms removed as previously dis-

cussed. In the recursive case the equations become:

$$\hat{a}_k = \frac{1}{\alpha} C_k^H (r_k - G_k \tilde{b}_k)\,,$$

$$\hat{b}_k = \frac{1}{\beta} G_k^H (r_k - C_k \tilde{a}_k)\,,$$

15   where $\tilde{a}_k$ and $\tilde{b}_k$ are previous estimates of a_k and b_k, respectively. A flowchart

showing the method executed by a detector unit using this approach is shown in

FIG. 7. After initialization at 700, an update unit updates of $\hat{a}_k$ and $\hat{b}_k$ using

channel estimates $\hat{c}_k$ and $\hat{g}_k$, and prior detected values of $\tilde{a}_k$ and $\tilde{b}_k$ at step 701.

At step 702 a determination is made as to whether another iteration is needed. If

20   not, final values of $\hat{a}_k$ and $\hat{b}_k$ are output at 704. If so, current symbol values are

copied to prior detected values at step 703.

FIG. 8 shows a signal processing flow/block diagram for a symbol update unit around which a detector unit according to one embodiment of the invention can be build. The values $\hat{c}_k$ and $\hat{g}_k$ are reformed into C_k and G_k, respectively, by reformulation operators 801 and 802. Conjugation operators 803 and 804 provide

5   complex conjugate values. Logic such as that shown in FIG. 8 provides continuous, final estimates for the symbols. For symbol aligned signals, batch detection can be accomplished by calling a recursive detection unit once for each symbol time given the appropriate input values for each call.

Alternate detection approaches can be used. For example, rather than use

10   previously detected values for $\tilde{a}_k$ and $\tilde{b}_k$, these terms could be enumerated. Then, the chosen values of $\hat{a}_k$ and $\hat{b}_k$ will be determined by choosing hypotheses that correspond to the *best* metric. Another alternate detection approach is to compute the maximum a *posteriori* estimate of the possible transmit symbols. This is more complicated in that probabilities for each transmit symbol are esti-

15   mated during each iteration. U.S. patent 5,887,035, previously discussed and incorporated by reference, provides useful background that can be used to develop alternate detection approaches.

The recursive channel estimation problem at time k is to find estimates of $\hat{c}_k$ and $\hat{g}_k$ from the equation:

20   $$\hat{c}_k\hat{g}_k = \arg\min_{c_k g_k} | y_k - \hat{y}_k(a_k, b_k) |^2 .$$

Since joint estimation was previously shown to result in the single-user estimator with interference terms, an approach similar to that employed in detection must be used. The channel update is performed according to the equations:

$$\hat{c}_k = A_k^H (y_k - B_k \widetilde{g}_k) \, ,$$

$$\hat{g}_k = B_k^H (y_k - A_k \widetilde{c}_k)$$

where $\widetilde{c}_k$ and $\widetilde{g}_k$ are previous estimates of c_k and g_k, respectively. Since the interfering user's channel estimate must be known in order to find the new esti-

5 mate, values from prior iterations can be used to calculate these new estimates.

In the above approach, $\hat{c}_k$ and $\hat{g}_k$ depend only upon the single received sample vector y_k, which may be subject to noise and other signal interference. Since there typically is correlation in time from one sample to the next, channel tracking can be used. Consider the least-means-square (LMS) update for the

10 channel coefficient $c_1(k)$. In the case that the transmit diversity approach has two received samples at two different symbol times, $k \in \{2j, 2j+1\}$, the LMS updates are found using the following equations:

$$\hat{c}(2j+1) = \hat{c}(2j) + \mu a_1(k)^* e_1(k) \, ,$$

$$\hat{c}(2j+2) = \hat{c}(2j+1) - \mu a_2(k) e_2(k) \, .$$

15 A similar form exists for the other channel coefficients. Additional background on LMS tracking can be found in Haykin, *Adaptive Filter Theory*, third edition, Prentice Hall, 1996, which is incorporated herein by reference.

The term $\hat{c}_k$ is the update given a new estimate of $\hat{g}_k$. Using exponential smoothing, this update is written as:

20 $$\hat{c}_k = (1 - \mu)\widetilde{c}_k + \mu A_k^H (y_k - B_k \widetilde{g}_k) \, .$$

Letting:

$$e_k = y_k - A_k \hat{c}_k - B_k \hat{g}_k \, ,$$

gives the update:

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$$\hat{c}_k = \hat{c}_k + \mu A_k^H e_k,$$

giving LMS-like updates for the vector channel estimates. When no previous estimate for $\hat{c}_k$ is available, then estimates from previous time k-1 can be used to give:

5 $$\hat{c}_k = \hat{c}_{k-1} + \mu A_k^H e_k.$$

The update for $\hat{g}_k$ is similar.

A flowchart for the above approach is shown if FIG. 9. All vectors are initialized at step 900. At step 901, the update as described immediately above is performed. Steps 902 and 903 provide iteration. Once the iteration is complete, 10 channel tracking is performed at step 904 using the step size term as input. Final values are output at step 905.

FIG. 10 is a signal flow diagram for a channel estimation unit that is used in performing the method illustrated in FIG. 9. The values $\hat{a}_k$ and $\hat{b}_k$ are reformed into A_k and B_k, respectively, by reformulation operators 1001 and 1002. Conjuga-15 tion operators 1003 and 1004 provide complex conjugate values.

One approach for batch channel estimation is to assume that the channel is fixed so that joint least-squares (LS) estimation can be performed using multiple received samples. This approach can work well since there is no longer an undetermined system of equations that need to be solved. For example, if the re-20 ceived signals y_k through y_{k+N} are used to find the joint LS:

$$\begin{bmatrix} \hat{c}_k \\ \hat{g}_k \end{bmatrix}_{LS} = \left(\begin{bmatrix} A_k & B_k \\ A_{k+1} & B_{k+1} \\ \vdots & \vdots \\ A_{k+N} & B_{k+N} \end{bmatrix} \right)^+ y_k,$$

where $()^+$ is the pseudo-inverse operation. Since the symbol terms may not be able to be pre-computed, a recursive approach may be desired. In this case, the recursive channel tracking approach described above can be used for each symbol.

5   An alternative approach is needed when the two transmitted user signals are flat faded, but have misaligned symbol timing from each other at the receiver, resulting in intersymbol interference (ISI) from one signal to the other. This ISI appears, even in flat fading, since the pulse-shape responses are aligned so that they no longer have the same zero crossings. With dispersion, sampling the received signal at a higher, but uniform, sampling rate helps make the resulting re-

10   ceiver more tolerant to ISI. A higher sampling rate is required in the case where the medium response is not flat faded and significant dispersion results.

For the scenario above, non-uniform sampling at a rate greater than the symbol rate, but taking into account transmit diversity is used. The approaches

15   discussed previously are modified so that they can be used in this case. Sequence estimation approaches can be modified for use with multi-user transmit diversity, but the same method as previously described for recursive channel estimation is not used. Instead, batch estimation and a sub-optimal, recursive form for detecting symbols and computing channel estimates is employed.

20   Consider the two-user system described previously, now with symbol misalignment. The received signal is now sampled twice, each sampling time being optimal to one of the transmitted signals in the sense that no own-signal ISI is present for the corresponding signal. Let the sequences of samples for the first signal be represented as $\{r_k^a\}$ and $\{y_k^a\}$. Similarly, the sequences of samples for

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the second signal are $\{r_k^b\}$ and $\{y_k^b\}$. The signals $\rho_a(j)$ and $\rho_b(j)$ are introduced to represent the pulse-shape response for the first and second signals, respectively. The received signals are then written as:

$$r_k^a = C_k a_k + G_k u_k^a + \omega_k^a ,$$

5
$$r_k^b = C_k u_k + G_k b_k^b + \omega_k^b ,$$

and:

$$y_k^a = A_k c_k + \Gamma_K^b g_k^a + v_k^a ,$$

$$y_k^b = \Gamma_K^a c_k + B_k g_k + v_k^b .$$

Terms listed below are given by:

10
$$u_k^a = \sum_j \rho_a(j) a_{k+j} ,$$

$$u_k^b = \sum_j \rho_b(j) b_{k+j} ,$$

$$\Gamma_k^b = \sum_j \rho_a(j) A_{k+j} ,$$

$$\Gamma_k^a = \sum_j \rho_b(j) B_{k+j} ,$$

where the summations above are taken over significant non-zero components of

15   the pulse shape response terms.

In batch mode, detection is performed in the same manner as in the synchronous case. For each symbol time k, the detection approach is used to update $\hat{a}_k$ and $\hat{b}_k$. The ordering of k does not necessarily have to be in natural order $\{1,2,...,K\}$. After detection, channel estimation is performed using the approach

20   described below. Because of the nature of the channel fading process, updates in natural order are assumed for the recursive channel estimation approach.

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For detection, the terms u_k^a and u_k^b are composed of prior, detected symbol values from the kth as well as other symbols from times $j \neq k$. A flowchart for this approach is shown in FIG. 11. The form of this flowchart is similar to previous flowcharts, with initialization taking place at step 1100, iteration being handled by

5   steps 1102 and 1103, and final values being output at 1104. Now, however, step 1101 is a process that performs the symbol update based upon the following equations:

$$\hat{a}_k = \frac{1}{\alpha} C^H (r_k^a - G_k u_k^b),$$

$$\hat{b}_k = \frac{1}{\alpha} G^H (r_k^b - C_k u_k^a).$$

10   The interfering terms are composed of symbols from prior iterations and the pulse shape component. FIG. 12 shows a signal processing flow diagram of a symbol update unit that can be used to perform step 1101 in the flowchart of FIG. 11. The symbol update unit includes reformulation operators 1201 and 1202 and conjugation operators 1203 and 1204 as before. In this case however, calculation units

15   1205 and 1206 calculate values for the u terms. The interconnections between various other components such as adders and multipliers are shown in the figure.

A recursive channel estimator uses a form similar to that of the synchronous case, and is described by the equations:

$$\hat{c}_k = \hat{c}_{k-1} + \mu_a A^H (y_k^a - \Gamma_k^b g_k),$$

20   $$\hat{g}_k = \hat{g}_{k-1} + \mu_b B^H (y_k^b - \Gamma_k^a c_k).$$

FIG. 13 is a flowchart for the recursive channel estimation. Stored values are initialized at step 1300. At step 1301, the update the update according to the above equations is performed. Steps 1302 and 1302 provide iteration. Once the itera-

tion is complete, channel tracking is performed at 1304 using the step size term as input. Final values are output at step 1305.

FIG. 14 is a signal processing flow diagram for the update unit that performs the update at step 1301 in FIG. 13. This unit includes operators similar to those previously discussed, including reformulation operators 1401 and 1402 and conjugation operators 1403 and 1404.

A recursive approach can be used with transmit diversity where there is ISI. For the update of the symbols the same detection unit described above is used, but with the following changes. In performing the update of $\hat{a}_k$ using received data sample y_k^a, the interference terms u_k^b are made up of hypothesized and/or feedback values of the terms $\tilde{b}_j$. From these hypothesized values, different estimates of $\hat{a}_k$ and $\hat{b}_k$ result, and the values that lead to the best metric are detected. Once each symbol is detected at update time k, the recursive approach above is used to perform channel tracking. The detected symbols are used for channel tracking, along with any undetected (hypothesized) symbols that can be obtained from the chosen hypotheses.

In the case that conventional transmission is used with systems that also contain transmit diversity, the invention can still be used. Assume one signal, say a_k, is a traditional transmission, and the interferer uses transmit diversity. In this case, assuming a_1 and a_2 are transmitted at consecutive symbol times corresponding to the transmit diversity symbol time k, then term y_k replaces A_k and c_k as follows:

$$y_k = \begin{bmatrix} a_1 & 0 \\ a_2 & 0 \end{bmatrix} \begin{bmatrix} c_1 \\ 0 \end{bmatrix} + B_k g_k + v_k .$$

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Replacing r_k, C_k, and a_k results in:

$$r_k = \begin{bmatrix} c_1 & 0 \\ 0 & c_1^* \end{bmatrix} \begin{bmatrix} a_1 \\ a_2^* \end{bmatrix} + G_k b_k + \omega_k .$$

The above forms can be used for detection and channel estimation according to the invention in a mixed scenario.

5   It is also important to understand that the invention can be applied where there are more than two users. In such cases, the technique is applied to two users at a time. Such would be the case, for example, with a multi-input, multi-output (MIMO) system with many users.

     FIG. 15 is a block diagram of a mobile terminal that implements the invention. 10 tion. FIG. 15 illustrates a terminal with voice capability, such as a mobile telephone. This illustration is an example only, and the invention works equally well with mobile terminals that are dedicated to communicating with text or other forms of data. Some types of mobile terminals may not contain all of the components shown in FIG. 15. As shown in FIG. 15, the terminal includes radio block 1501, a 15 baseband logic block, 1502, control logic block 1503 and an audio interface block, 1504. Within radio block 1501, the receive and transmit information is converted from and to the radio frequencies (RF) of the various carrier types, and filtering is applied, as is understood in the art. Radio block 1501 includes the preprocessor previously discussed. The terminal's antenna system, 1507, is connected to the 20 radio block. In baseband logic block 1502, basic signal processing occurs, e.g., synchronization, channel coding, decoding and burst formatting. In this example, the baseband logic includes a channel estimation unit, 1512, and a detection unit, 1513, according to the invention. The baseband logic block can be implemented by one or more ASIC's, or perhaps by a digital signal processor (DSP). Audio in-

terface block 1504 handles voice as well as analog-to-digital (A/D) and D/A processing. It also receives input through microphone 1505, and produces output through speaker 1506. Control logic block 1503, coordinates the aforedescribed blocks and also plays an important role in controlling the human interface compo-

5   nents (not shown) such as a key pad and liquid crystal display (LCD). The functions of the aforedescribed transceiving blocks are directed and controlled by one or more microprocessors or digital signal processors such as main processor 1508, shown for illustrative purposes. Program code, often in the form of microcode is stored in memory 1509 and controls the operation of the terminal

10   through the processor or processors. The mobile terminal illustrated in FIG. 15 interfaces to a smart card identity module (SIM), 1511, through a smart card reader interface. The interconnection between the main processor, control logic, memory, and SIM is depicted schematically. The interface is often an internal bus.

15   A mobile terminal implementation of the invention does not have to be a traditional "cellular telephone" type of terminal, but may include a cellular radio-telephone with or without a multi-line display; a personal communications system (PCS) terminal that may combine a cellular radiotelephone with data processing, facsimile and data communications capabilities; a personal data assistant (PDA)

20   that can include a radiotelephone, pager, Internet/intranet access, Web browser, organizer; and a conventional laptop and/or palmtop computer or other appliance that includes a radiotelephone transceiver. Mobile terminals are sometimes also referred to as "pervasive computing" devices.

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Specific embodiments of an invention are described herein. One of ordinary skill in the networking and signal processing arts will quickly recognize that the invention has other applications in other environments. In fact, many embodiments and implementations are possible. In addition, the recitation "means

5   for" is intended to evoke a means-plus-function reading of an element in a claim, whereas, any elements that do not specifically use the recitation "means for," are not intended to be read as means-plus-function elements, even if they otherwise include the word "means." The following claims are in no way intended to limit the scope of the invention to the specific embodiments described.

10   What is claimed is: